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INJURIES OF PERIPHERAL NERVES.

War gives a stimulus to the study of injuries of peripheral nerves, and the number of significant contributions to the literature of this subject has been greatly increased during the last few years. In England, peripheral nerve centres have been set up for the investigation and treatment of patients with nerve injuries, and have proved to be very successful. Since the patients for whom they cater require thorough and special investigation both before and after operation, rather than emergency surgery, they are well suited for treatment in a special centre.

At the same time the surgeon who first handles a man with a peripheral nerve injury does important work in obtaining an early assessment of the damage done and, when possible, in suturing the nerve. The present article therefore includes sections on the early diagnosis of nerve injuries and primary suture of nerves as well as a discussion of later management such as might be undertaken at a peripheral nerve centre. A paragraph summarizing the details of nerve regeneration is also included.

Regeneration of a Peripheral Nerve.

A study of regeneration of divided peripheral nerves throws some light on the principles which should guide the surgeon who attempts to assist this process. The essential stage in spontaneous recovery is the downgrowth of nerve fibres from the central stump and their gradual progress to the end-organs which the nerve originally supplied. When the median nerve is divided at the wrist, the regenerating fibres have to grow down for a distance of inches, whereas if the sciatic nerve is divided in the gluteal region, the central portion must gradually extend down the whole leg. Growth of the nerve fibres occurs at the rate of from one to two millimetres a day, but it is obvious that there are many difficulties in the way of full regeneration:

1. The initial difficulty is for the central outgrowth to make a connexion with the distal stump. There is apparently no neurotropic influence guiding it in the right direction; it merely grows forward from the central end of the nerve, and if there is a large gap in the nerve or if the tissues are extensively disorganized, a connexion may never be made. There is a possibility that some guidance is given by an outgrowth of Schwann cells from the peripheral segment. These cells extend in the form of strands towards the central stump, and it is supposed, but not proved, that the growing axones are guided to the distal portion of the nerve by such strands.

2. Anything which stimulates fibrosis at the region of the gap in the nerve increases the difficulty of regeneration of the nerve, for the axones grow slowly through fibrous tissue. Infection is therefore unfavourable to regeneration.

3. The peripheral elements undergo irreversible degenerative changes after some time. Most of the patients in whom there is a satisfactory spontaneous recovery of nerve function have shown improvement within the first six months. The central process can, however, send out regenerating nerve fibres for at least a year, and, although changes in peripheral structures modify the quality of regeneration, they do not prevent it absolutely for two years.

4. It is apparently a matter of chance whether a given central process makes contact with an appropriate end-organ. Thus a process originally supplying a certain muscle may, during regeneration, make a connexion with a sensory end-organ. The degree to which this disability can be overcome by "reeducation" is not known.

Regeneration is not complete when new nerve fibres have grown down to the end-organ: restoration of function can occur only when these fibres are of correct size and fully medullated, so that they can carry impulses of the appropriate frequency and velocity.

It will be readily appreciated that the recovery of function in a divided nerve is never complete. The prognosis is much better for a purely motor or purely sensory branch than for a mixed nerve.

Early Diagnosis of Peripheral Nerve Injuries.

Fractures and wounds of soft parts are sometimes complicated by injury to a peripheral nerve, and the latter is often overlooked when the wound is first examined and treated. Whenever possible, the routine examination of any recent wound should include simple tests for loss of power and sensation peripheral to the wound. The presence of a fracture may, of course, prevent such examination; on the other hand, certain fractures such as those of the shaft of the humerus at once suggest the possibility of as associated nerve lesion.

Every surgeon called on to treat wounds should be familiar with the signs of injury to the following nerves: radial, ulnar and median in the upper extremity; posterior tibial and common peroneal in the lower extremity.

One difficulty in testing the motor elements of these nerves is the existence of so-called trick movements. Thus the median and ulnar nerve innervate the flexors of the wrist, but some flexion of the wrist is, nevertheless, possible when both these nerves have been paralysed. It can be brought about by the long abductor of the thumb and, similarly, flexion of the fingers can result from extension of the wrist. Certain diagnostic signs can be chosen to eliminate these difficulties and are important for that reason. They are:[1][7] (*a*) In lesions of the radial nerve the patient is unable to extend the proximal phalanx of the thumb or fingers, and unable to abduct the thumb in the plane of the palm. (*b*) In lesions of the ulnar nerve in the arm the patient cannot flex the tip of the little finger; he cannot flex the proximal phalanx of the ring or little finger, while the distal phalanges remain extended; and he cannot move the extended middle finger laterally; only the last of these three tests is applicable if the lesion is in the forearm. (*c*) In lesions of the median nerve in the arm the patient cannot flex the distal phalanx of the index finger or of the thumb and he cannot oppose his thumb and little finger; the patient fails in the last test when the lesion is in the forearm, except when, as occasionally happens, the ulnar innervates the *opponens pollicis* muscle.[6] (*d*) In lesions of the external popliteal nerve the patient cannot evert the foot.

In testing for the appreciation of pin prick or other sensory stimulus one must guard against errors caused by the overlapping of areas supplied by adjacent sensory nerves. This overlap occurs, of course, along the borders of the region to which a nerve is distributed; thus, in lesions of the ulnar nerve, sensation is always abolished

from the distal phalanges of the little finger, even though the adjacent side of the ring finger, which is also supplied by the ulnar nerve, may still retain some sensation through overlap of the median nerve. The distal areas to which the sensory nerves are distributed are as follows: (*a*) the ulnar nerve supplies the little finger, half the ring finger and the ulnar border of the hand; (*b*) the median nerve supplies the outer two thirds of the palm and the palmar aspects of corresponding fingers and thumb, whilst it also supplies the index, middle and ring fingers on their dorsal aspects; (*c*) the radial nerve supplies the posterior surface of the thumb and the adjacent part of the dorsum of the hand, but lesions of this nerve rarely cause loss of sensation from more than a small area at the base of the thumb; (*d*) the external popliteal nerve supplies the dorsum of the foot and the lower two-thirds of the outer side of the leg; (*e*) the internal popliteal nerve supplies the sole of the foot and the heel.

Primary Nerve Suture.

Primary nerve suture was condemned as a result of the experience in the Great War, but later became a recognized procedure in the early repair of clean civilian wounds. It will not often be possible in war wounds, but may be carried out whenever healing by first intention is likely. It is also a reasonable argument that if a wound has had to be explored and a divided nerve is found, then nothing is lost by suturing that nerve even if the wound does subsequently become infected. It is obvious, however, that a nerve cannot be sutured in a wound already infected.

Detailed Investigation of a Patient with a Peripheral Nerve Lesion.

As already suggested, it is not common in wartime for a patient to have a nerve injury detected and treated successfully at the time of wound excision. More usually treatment of the nerve lesion has to be postponed because of a serious associated injury such as a fracture, or because of infection, or even because the damage to the nerve is overlooked. The patient therefore becomes a candidate for delayed nerve suture.

Thorough investigation of the lesion is essential before treatment can be attempted. One important aim of this investigation is the recognition of spontaneous recovery, and it is therefore desirable that records of motor and sensory function should be made soon after the injury and should be added to regularly. The full examination of peripheral nerve function includes the following four types of test.

Test of Motor Power.

Test of motor power has already been described so far as it is applied to a recently injured patient, but in other circumstances it has to be carried out in very much more detail. An atlas has been drawn up by the Nerve Injuries Committee of the Medical Research Council showing the methods of testing for paralysis of various muscles of the body.[8] Reproductions of over fifty photographs illustrate how the tests should be carried out, and short legends indicate the spinal segments and the peripheral nerve by which the muscle is supplied. The accuracy of a few points raised in this booklet has been questioned by a reviewer, but the work is undoubtedly a valuable guide for "those less experienced in the examination of patients with lesions of peripheral nerves".

It has been pointed out in a recent paper that the *flexor pollicis brevis* muscle may sometimes be innervated by the ulnar rather than the median nerve.[9] Now, the movement of abduction of the thumb in a plane at right angles to the palm is produced mainly by this muscle and the *abductor pollicis*, and is one of the classical signs of median nerve function. The test is frequently carried out by laying the patient's hand flat on a table with the palm uppermost, and asking him to try to touch with the tip of his thumb a pencil which is held vertically above the thumb. This test is misleading in those cases in which the *flexor pollicis brevis* is innervated by the ulnar nerve, and patients may sometimes be considered to have an intact or recovering median nerve when it is actually severed and requires suture. One means of investigating an injury of the median nerve when some activity remains in those thenar muscles which may be supplied by either median or ulnar, is to block the ulnar by injecting a few cubic centimetres of a 2% solution of "Procaine" around the nerve near the medial epicondyle.

The Test of Sensation.

In the test of sensation the patient should be warm, comfortable and quiet, and should understand the general purpose of the examination. The sensory areas supplied by the various nerves are illustrated in the memorandum referred to above.

Examination for Trophic Changes.

The most striking feature of trophic changes is a glossiness of the skin, with disappearance of the normal folds and ridges. The skin may be very dry and covered with a branny desquamation that maps out the area, but sometimes sweating is increased and beads of sweat appear on the glossy skin. In other cases the whole surface is sodden and offensive, and is covered by a thick layer of cutaneous *débris*. Any vascular changes present are made obvious by a cyanotic or deep red colour.[11]

Test for the Electrical Reactions of the Muscles.

The testing of the electrical reactions of the muscles supplements the previous tests and provides a means of differentiating an hysterical paralysis or anæsthesia from an organic lesion. It is customary to use both faradic and galvanic currents, the terminals being a small pad placed over the motor point of the muscle and a large pad placed at some neutral point. The normal muscle gives a quick response to each form of current, but if the nerve has been divided for ten days or more the reaction of degeneration is obtained. In this condition there is no response at all to a faradic current, and the galvanic current causes a characteristic slow undulatory contraction, which is shown best when the terminals are placed towards the two ends of the muscle.

Some workers prefer to test the electrical reactions by means of a condenser set, in order to eliminate variations in voltage, duration of the impulse, and rate at which the impulse is delivered.

Decision Regarding Operation.

The examinations described above are carried out at regular intervals and an opinion is formed as to whether the nerve is recovering spontaneously and whether operation is required. The following have been suggested as criteria for determining the necessity for operation:[12] (*a*) persistence of signs indicating that a nerve has been completely severed; (*b*) palpation of a thickened mass in a nerve at the site of injury; (*c*) cessation of improvement at a stage where the recovery is inadequate.

The ideal time for operation is influenced by several factors: (*a*) the wound must be soundly healed so that there is no danger of activating latent infection; (*b*) it must be reasonably certain that spontaneous recovery is unlikely; (*c*) the sooner a divided nerve is sutured, the less chance is there for the occurrence of irreparable damage to the end-organs.

Various surgeons have laid down arbitrary periods of several months before the lapse of which operation should not be undertaken. The issues concerned have become much clearer as a result of the following classification of the nerve injuries that cause loss of function:[13] (*a*) complete anatomical division of a nerve; (*b*) a lesion in which more or less of the supporting structure is preserved, but in which there is nevertheless such disturbance of the nerve fibres that true Wallerian degeneration occurs; and (*c*) a transient block, often incomplete, never followed by Wallerian degeneration and always resulting in rapid and complete recovery. The awkward names given to these three types—neurotmesis, axonotmesis and neuropraxia—have been criticized but not successfully replaced, and the classification itself has been ably defended.[13]

Now, in neurapraxia operation is not required; spontaneous recovery is perfect and fairly rapid, beginning usually after about two weeks and reaching completion after about eight weeks. The condition is recognized by

the following characteristics: (*a*) the paralysis is predominantly motor; (*b*) there is little wasting, and the electrical reactions of the muscles are normal; (*c*) subjective sensory disturbances such as numbness, tingling and burning are common; (*d*) sensations of temperature, pain and touch are only slightly impaired, but loss of postural sensibility and vibration sense is common; and (*e*) loss of sweating is unusual.

Operation is also contraindicated in a lesion which merely interrupts the axones, but is required when the nerve is completely divided. These two conditions cannot be distinguished clinically by the signs of nerve involvement and the surgeon who is trying to determine the necessity for operation is guided by three factors: (*a*) The cause of the injury may suggest the diagnosis; radial paralysis following a gunshot wound of the arm is likely to be due to a complete severance of the nerve; a similar paralysis associated with a closed fracture of the humerus is probably due to a lesion which has interrupted only the axones. (*b*) One may wait and watch what happens, taking care in the meanwhile to avoid overstretching of paralysed muscles, ankylosis of joints, or undue wasting of the limb. Sufficient time is given for regeneration to occur, and then, if necessary, operation is undertaken. (*c*) The method just described has been the classical procedure, but, since signs of recovery are sometimes delayed for about six months, the tendency has been to wait for very long periods; a better policy is to make an exploratory incision in those cases in which signs of recovery have not occurred within the time calculated as necessary for recovery. In this way valuable weeks may be saved; no harm is done if a conservative incision is made by a competent surgeon and the nerve is examined directly. In some cases it will be easy to decide what to do; in others use of electrical stimulation of the exposed nerve will show that regeneration has occurred; there still remain some, however, in which the continuity of the nerve is preserved, but the likelihood of return of function is difficult to assess.

Late Operation for Repair of a Defect in a Peripheral Nerve.

Types of Operation Available.

The methods for repairing gaps in peripheral nerves can be divided into three classes.[8]

End-to-End Anastomosis.

End-to-end anastomosis is always the method of choice. If the gap is large preliminary measures must be taken to make end-to-end anastomosis possible. These are: (i) Mobilization, in which the nerve is freed from the surrounding tissues for a considerable distance both above and below the lesion. It may include stripping up, or even sacrificing motor branches, which by their tension prevent the approximation of the stumps. (ii) Transposition, in which the stumps are brought closer together by moving the nerve into a shorter course. (iii) Nerve stretching, in which the stumps are sutured under tension. The nerve is stretched either by passive manipulation at operation or by suturing it while the appropriate joints are flexed and then extending the limb in stages after the operation. The length of nerve mobilized may be safely increased not more than 10% by stretching.[9] (iv) Bone resection in which the gap between the nerve ends is diminished by resecting a segment of bone. This is too radical for use except as a last resort. It was employed recently by Dandy who removed eight centimetres of bone from the upper half of the humerus in a young girl.[10] The left arm had been cut by a piece of flying glass midway between the axilla and the elbow and all the important nerves had been severed.

By employing a combination of the first three of these methods it is possible to close large gaps in nerves. The maximum lengths which can be successfully closed by end-to-end anastomosis have been given different values by different authors. In a series obtained recently on patients with gunshot, lacerated or incised wounds, the maximum resections of nerves that were followed by some recovery were as follows:[9] combined sciatic, 8·5 centimetres; medial popliteal, 6·0 centimetres; lateral popliteal, 9·0 centimetres; median, 7·0 centimetres; ulnar, 11·0 centimetres; radial, 6·0 centimetres. The same authors studied traction lesions of the lateral popliteal nerve, and showed that post-operative stretching can produce a lesion similar to that resulting from accidental trauma. This explains the failure of recovery in some patients from whom large segments of nerve were resected and an end-to-end anastomosis carried out. If a resection of more than ten centimetres is required in the lateral popliteal nerve, suture is not justified and alternative methods such as nerve grafting should be employed. With further work it should be possible to lay down similar limits of tolerance for resections in other nerves. It has already been tentatively suggested that these limits are: 15 centimetres in the main trunk of the sciatic; 12 centimetres in the median or ulnar; and 8 centimetres in the radial.[11] It is probable, however, that the maximal resection compatible with recovery depends not only on the nerve involved, but also on the site of suture. If the suture overlies an acutely flexed joint, the degree of damage from stretching may be more extensive than in other situations.

Bridge Operations.

There are certain nerves in which end-to-end anastomosis is often impossible: (*a*) the digital nerves; (*b*) the brachial plexus, especially the fifth and sixth cervical segments where mobilization is very difficult; (*c*) the lateral popliteal nerve, particularly when it has been extensively resected after traction lesions; and (*d*) the facial nerve in the temporal canal. In these cases some form of bridge operation may be undertaken.

The most successful type of bridge operation is the autograft. The diameter of the graft must equal or exceed that of the host nerve, and this means that cable grafts have to be used. Autografts survive and the axones and neurilemma sheaths undergo Wallerian degeneration in the same way as the peripheral stump. The graft then conducts new fibres to the periphery almost as well as the peripheral stump itself. By the time the axones arrive at the distal part of the nerve, Schwann cells have bridged the connexion between this and the graft, and the axones grow on without interruption. Although most surgeons have some confidence in the value of cable autografts, the number of patients in whom they have been successfully used is still small.

Homografts have not so far been successful, while heterografts, nerve flaps, *suture à distance*, and tubulization are not recommended. An occasional success has been obtained with double lateral implantation, a procedure in which the resected nerve ends are implanted into a slit made in an adjacent nerve. The proximal end then grows down to the distal end through this nerve.

Nerve Crossing.

A nerve may be deliberately severed and the central end attached to the peripheral end of one that has been divided by injury. This procedure has only a limited application, partly because of the difficulty of finding a non-essential nerve adjacent to the injured nerve, and partly because a movement acquired by nerve crossing cannot be readily controlled.

Suture Material.

Care must be taken to avoid damage to the nerve fibres when suturing, and therefore a very fine suture material is used and passed only through the nerve sheath. The material should be non-absorbable, as otherwise it provokes a severe tissue reaction. Catgut of size "0000" has sufficient tensile strength for nerve suture, but has been given up as being too coarse and too irritating, and fine linen, fine white silk and human hair have been substituted.

An alternative method is now available in which the segments of the nerve are held in apposition by fibrin. A pool of plasma is placed around the nerve ends and made to clot. Provided there is no tension at the site

of junction the fibrin acts as an efficient suture material; it is non-irritating and favourable to the regeneration of nerve fibres.[11] [12]

This method has no application to cases in which suture has to be made under tension, and is therefore usually unsuitable for secondary suture. It is used mainly for primary suture and for cable grafts. It is particularly useful in the latter instance, for fresh nerve grafts are so soft and slippery that they are difficult to handle and suture. The indications for fibrin suture have been laid down as follows: (i) There must be little or no tension at the suture line. (ii) There must be no great disparity in the size of the surfaces that are to be opposed. Otherwise a better result is obtained with ordinary methods. (iii) The nerve ends should lie in a situation where plasma can collect and form a small pool. A "Latex" mould has been used by some American workers to overcome this difficulty by holding the nerve ends in apposition while the plasma clots around them.[13] It permits the fibrin to encircle the junction and can be used where fibrin suture would otherwise be difficult. (iv) Plasma is sometimes valuable when the stumps are rather inaccessible.

Technique of Operation.

It is necessary to find the nerve above and below the site of injury and not to search for it in the scar tissue in the region of the wound. The amount to be resected is sometimes difficult to gauge. In general, the nerve is cut back to a level at which the bundles of fibres can be seen standing out as gelatinous points free of fibrous tissue. Excess of fibrosis in the distal end is probably more harmful than it is in the proximal segment; in the former case it prevents the axones from making their peripheral connexions, but in the latter case it appears to have little strangulating action on the downgrowing fibres. When resection is complete a junction is effected by one of the methods already described. Complete hæmostasis is essential, for effused blood leads to the formation of new fibrous tissue.

In some cases the nerve is exposed and found to be intact. It is then freed from scar tissue so that its mobility is restored. If compression and irritation have existed for so long that interstitial neuritis has resulted, there is little chance of recovery, but further damage may be prevented.

Post-Operative Treatment.

Experimental work has demonstrated that the strength of a suture line in nerves rises to a maximum in about three weeks. During this period the limb has to be postured so that there is no extra strain on the sutures, and during the following three or four weeks it is gradually straightened. Posturing of paralysed muscles has to be kept up for a very much longer time, namely, until reinnervation has occurred. This is not incompatible, however, with daily movements of the limb. In the adult, the metacarpo-phalangeal joints and the interphalangeal joints are especially liable to become stiff if they are kept fixed, even in the zero position. Full recommendations as to the best method of splinting the various parts have recently been published.[6]

An attempt is made to maintain nutrition of the paralysed muscles by the daily use of heat, massage and electrical stimulation. This treatment certainly has a beneficial psychical effect, whatever its direct influence on the limb.

Assessment of Recovery in Peripheral Nerve Injuries.

The assessment of recovery in peripheral nerve injuries is rather difficult. The statistics of recovery in nerve injuries treated in the Great War were so compiled that it is almost impossible to compare the results published by any two clinics. A scheme of assessment has recently been put forward, and has been accepted with minor modifications by the Nerve Injury Committee of the Medical Research Council. In brief the scheme is as follows:[14]

1. *Motor Recovery.*
   - Stage 0: no contraction.
   - Stage 1: flicker or trace of contraction.
   - Stage 2: active movement with gravity eliminated.
   - Stage 3: active movement against gravity.
   - Stage 4: active movement against gravity and resistance.
   - Stage 5: normal power.

2. *Sensory Recovery (in the autonomous zone, not in the area of overlap).*
   - Stage 0: absence of sensibility.
   - Stage 1: recovery of deep cutaneous pain sensibility.
   - Stage 2: return of some degree of superficial cutaneous pain and touch sensibility.
   - Stage 3: complete return of superficial cutaneous pain and touch sensibility, with disappearance of any over-response.
   - Stage 4: return of sensibility as in Stage 3, with the addition that there is recovery of two-point tactile discrimination.

The result of an examination of a patient is recorded in a form such as M.3, S.2.

Recovery following Peripheral Nerve Injury.

The recovery varies with different nerves. (*a*) Radial nerve: the best recovery is given by this nerve, possibly because it is mainly motor and supplies large muscles. It should be remembered, too, that many injuries of the radial nerve are associated with a fracture of the humerus and are of the nature of neuropraxia. (*b*) Ulnar nerve: the recovery is fair; if sensation to pin prick is restored, the hand can be strong and useful even though the intrinsic muscles remain weak; fine movements of the hand such as are required for playing the piano are, of course, seriously impaired. (*c*) Median nerve: the recovery is poor because of loss of sensation in the thumb and index. (*d*) Sciatic nerve: recovery of motor power in the calf muscles is usual, but the loss of sensation in the sole and the wasting of the foot are serious, for they render the foot liable to injury. (*e*) Posterior tibial nerve: injury to this nerve is often overlooked because all movements at the ankle joint remain normal; the sensory loss is eventually troublesome. (*f*) Common peroneal nerve: lesions of this nerve can be compensated for by the use of an appliance to prevent foot-drop.

References.

(1) H. Bailey: "Surgery of Modern Warfare", Chapter XLII, 1941.

(2) W. E. Dandy: "A Method of Restoring Nerves Requiring Resection", *The Journal of the American Medical Association*, Volume CXXII, May 1, 1943, page 35.

(3) Great Britain, Medical Research Council: War Memorandum, Number 7: "Aids to the Investigation of Peripheral Nerve Injuries", 1942.

(4) W. B. Highet: "Innervation and Function of the Thenar Muscles", *The Lancet*, February 20, 1943, page 227.

(5) W. B. Highet: "Splintage of Peripheral Nerve Injuries", *The Lancet*, May 9, 1942, page 555.

(6) W. B. Highet and W. Holmes: "Traction Injuries to the Lateral Popliteal Nerve and Traction Injuries to Peripheral Nerves after Suture", *The British Journal of Surgery*, Volume XXX, January, 1943, page 212.

(7) L. J. Pollock: "Evaluation of Incapacity Produced by Injuries of the Peripheral Nerves", *Surgery, Gynecology and Obstetrics*, Volume LXXIII, October, 1941, page 462.

(8) F. K. Sanders: "The Repair of Large Gaps in the Peripheral Nerves", *Brain*, Volume LXV, September, 1942, page 281.

(9) H. J. Seddon: "A Classification of Nerve Injuries", *British Medical Journal*, August 29, 1942, page 237.

(10) H. J. Seddon: "Classification of Nerve Injuries", *British Medical Journal*, October 10, 1942, page 438.

(11) H. J. Seddon and P. B. Medawar: "Fibrin Suture of Human Nerves", *The Lancet*, July 25, 1942, page 87.

(12) J. Swan: "Discussion on Injuries to the Peripheral Nerves", *Proceedings of the Royal Society of Medicine*, Volume XXXIV, June, 1941, page 521.

(13) I. M. Tarlov and B. Benjamin: "Plasma Clot and Silk Suture of Nerves", *Surgery, Gynecology and Obstetrics*, Volume LXXVI, March, 1943, page 366.

(14) J. Z. Young and P. B. Medawar: "Fibrin Suture of Peripheral Nerves: Measurement of the Rate of Regeneration", *The Lancet*, August 3, 1940, page 126.